Coherent Elastic ν-Nucleus Scattering with Cryogenic Crystal Detectors

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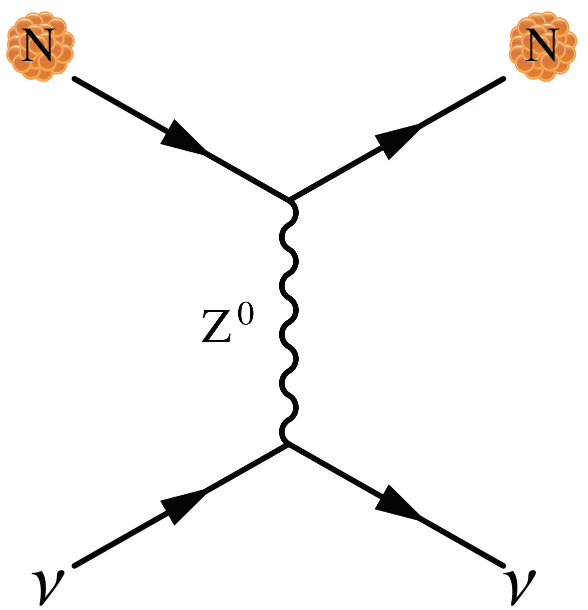
Overview

- Coherent Elastic Neutrino-Nucleus Scattering
- Neutrino Sources
- Why use phonon detectors?
- Ricochet at a Reactor
- Ricochet using electron capture source
- About the Neutrino Magnetic Moment
- Conclusion

Coherent Elastic ν-Nucleus Scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- σ: Cross Section
- T: Recoil Energy
- E_ν: Neutrino Energy
- G_F: Fermi Constant
- Q_W: Weak Charge
- M_A: Atomic Mass
- F: Form Factor



No flavor-specific terms!!!
Same rate for ν_e, ν_μ, and ν_τ

Why should we measure CE$\boldsymbol{\nu}$NS?

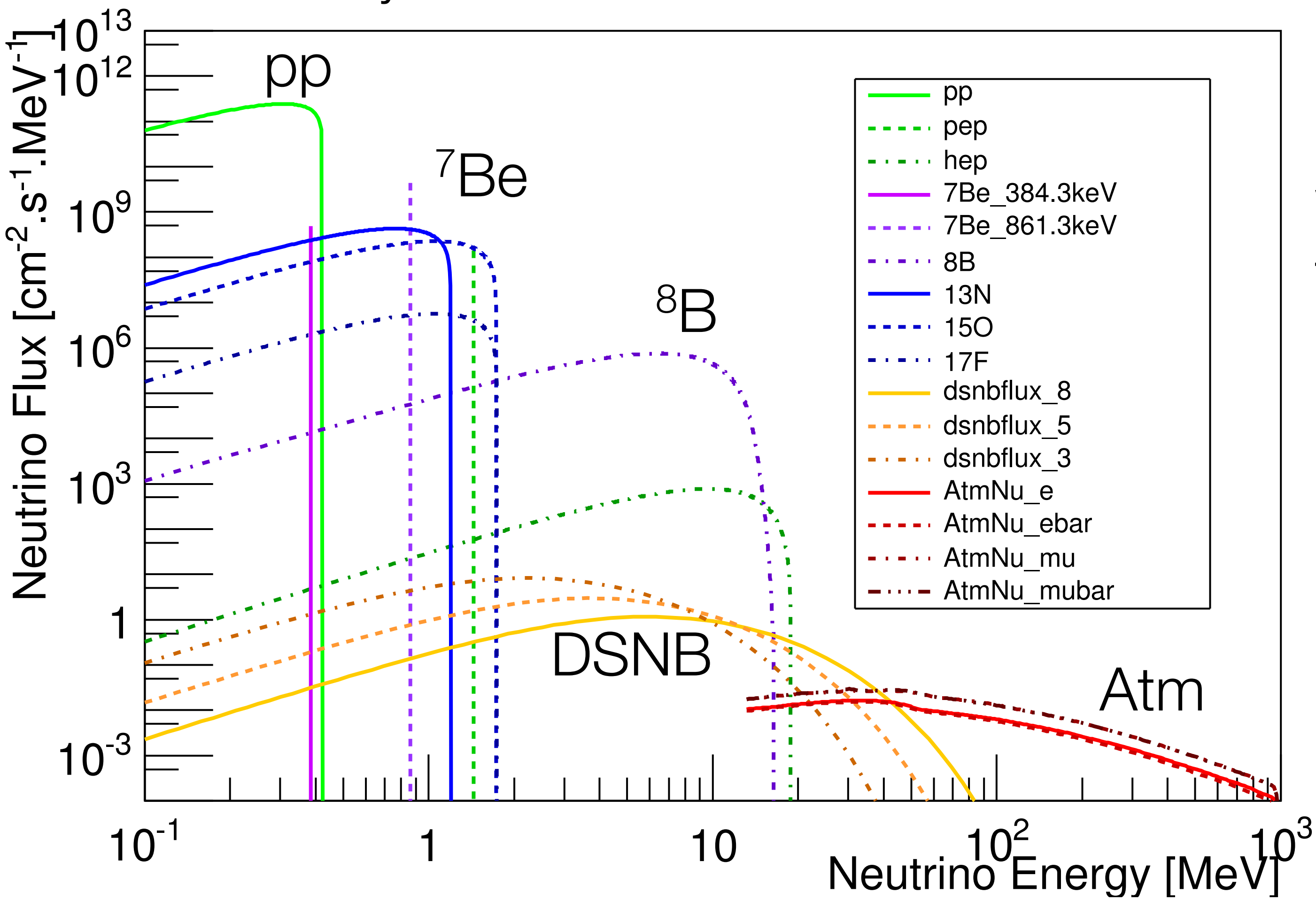
- Far reaching Physics program:
    - Sterile neutrinos, NSI, Weak Mixing Angle, Neutrino Magnetic Moments, SNe neutrinos are all potentially accessible through the CE$\boldsymbol{\nu}$NS channel
- CE$\boldsymbol{\nu}$NS will also be the dominant background for Dark Matter Direct Detection experiments - measuring this process demonstrates DM detector response to WIMPS
- CE$\boldsymbol{\nu}$NS offers a unique probe of Neutron Distribution Functions for Nuclear Physics (Form Factors)
- Expansion of the toolbox of the Neutrino Physics community
- Numerous synergies with other fields (direct dark matter detection, nuclear astrophysics, nuclear structure, $0\boldsymbol{\nu}\beta\beta$…)
- Active engagement of the theory community -- Coherent Theory Workshop, Raleigh, NC, January 2015, 30 attendees (http://coherent-theory.phy.duke.edu/)
- A unique opportunity to pioneer these measurements in the U.S.
- Overlapping Interest from nonproliferation community in small footprint detectors for cooperative monitoring of nuclear reactor cores

Neutrino Sources

4 sources to consider:

- The Sun + other cosmic sources
- Electron-capture sources
- Reactors
- Decay-at-rest sources

arXiv:1402.7137
1408.3581
1409.0050



G2 Dark Matter Experiments (SuperCDMS SNOLAB and possibly LZ) will be able to detect the Solar ^{8}B CE**v**NS signal!

Small number of events, but expect a positive CE**v**NS detection in the next ~5 years…

Neutrino Sources

4 sources to consider:

- The Sun + other cosmic sources
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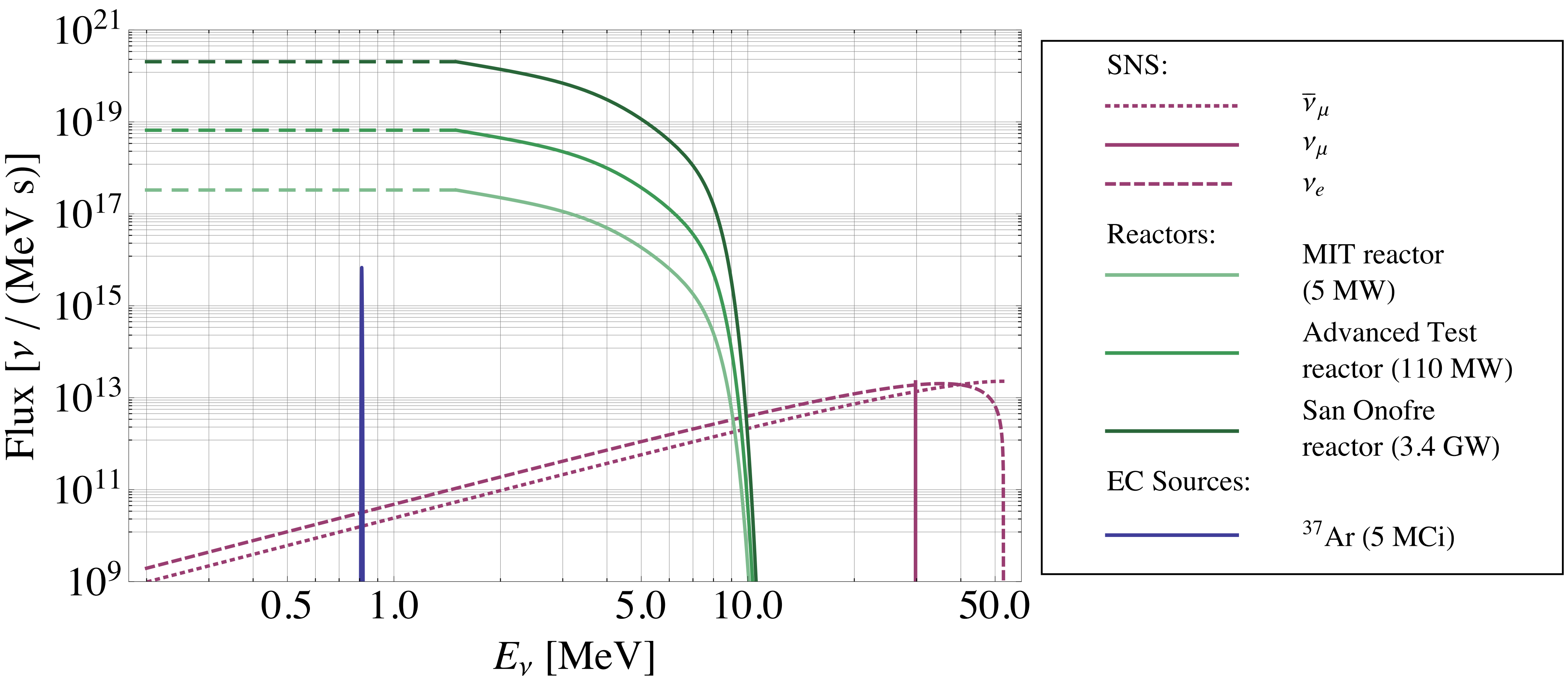
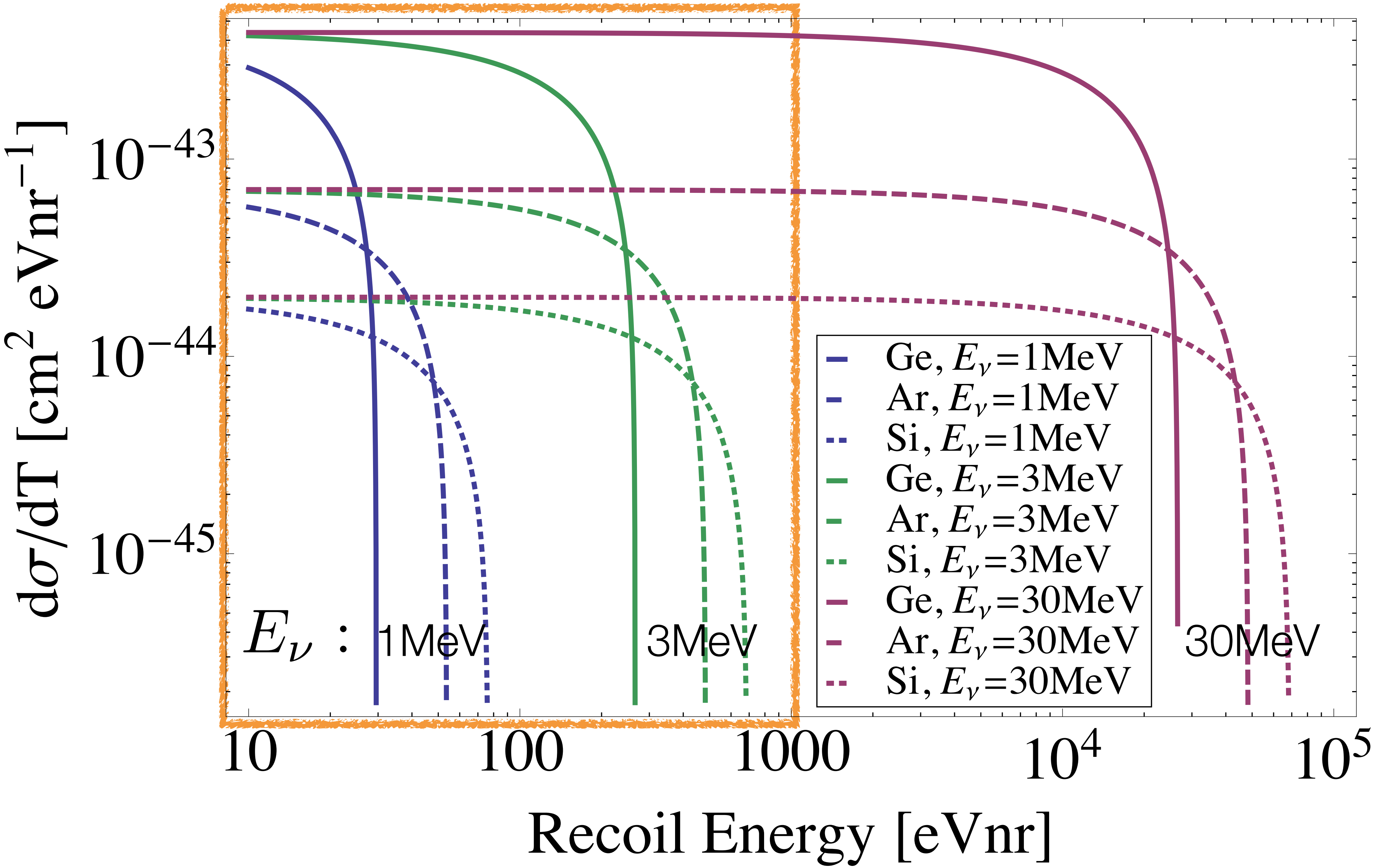


CEνNS Cross Sections

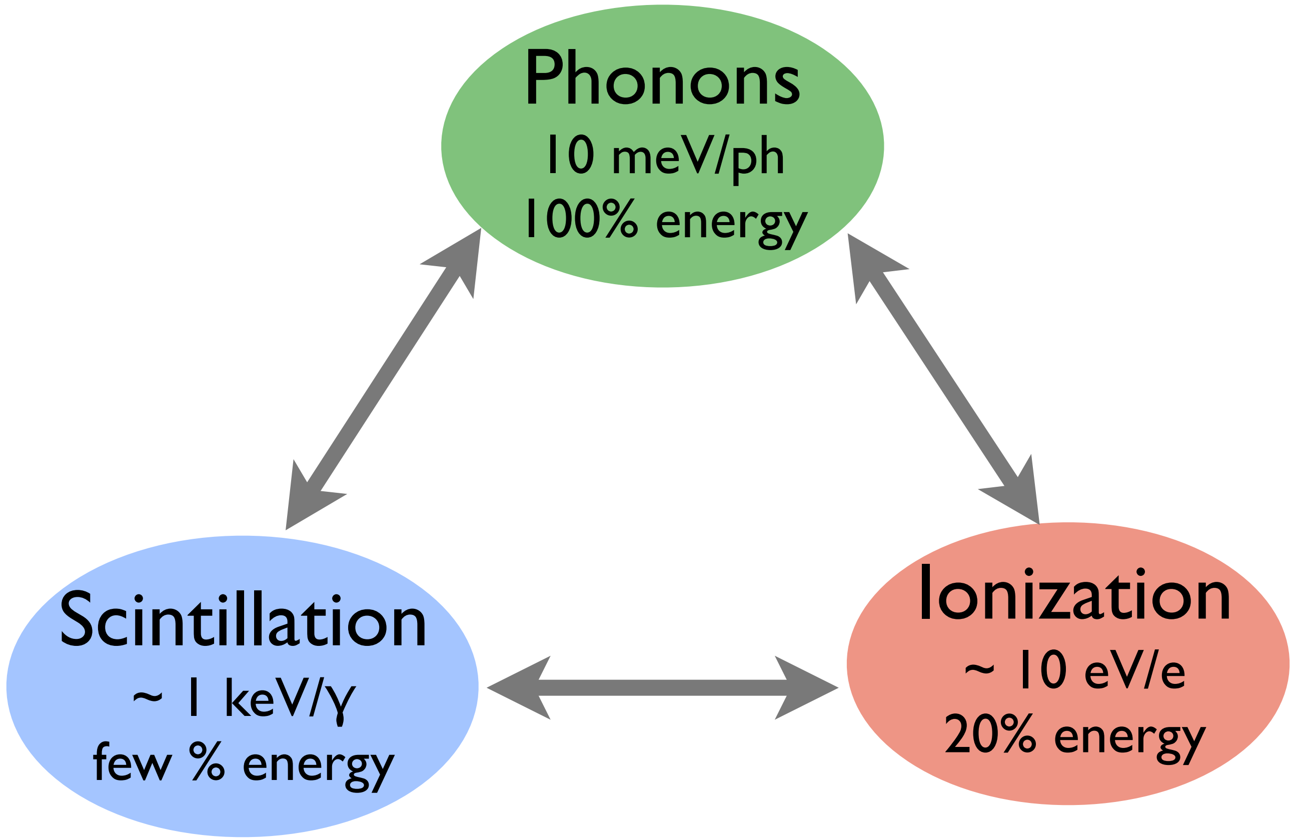
Phonon Sensors particularly useful in this range



Neutrino Sources

Sources	Pros	Cons
Electron Capture	Mono-energetic, can place detector < 1m from source, ideal for sterile neutrino search	< 1 MeV energies require very low (~10 eVnr) thresholds, 30 day half-life, costly
Nuclear Reactor	Free, highest flux	Spectrum not well known below 1.8 MeV, site access can by difficult, potential neutron background at research reactors, reactor rarely off for GW power plants
Spallation/Decay at Rest	Higher energies can use higher detector thresholds, timing can cut down backgrounds significantly	Lower flux than reactors. SNS currently has highest flux, with several proposals for larger machines in the works.

Low-energy recoils produce different products...



Multiple technologies are being developed that use one of more of these channels to detect CE**ν**NS

Phonon vs. Ionization Readout

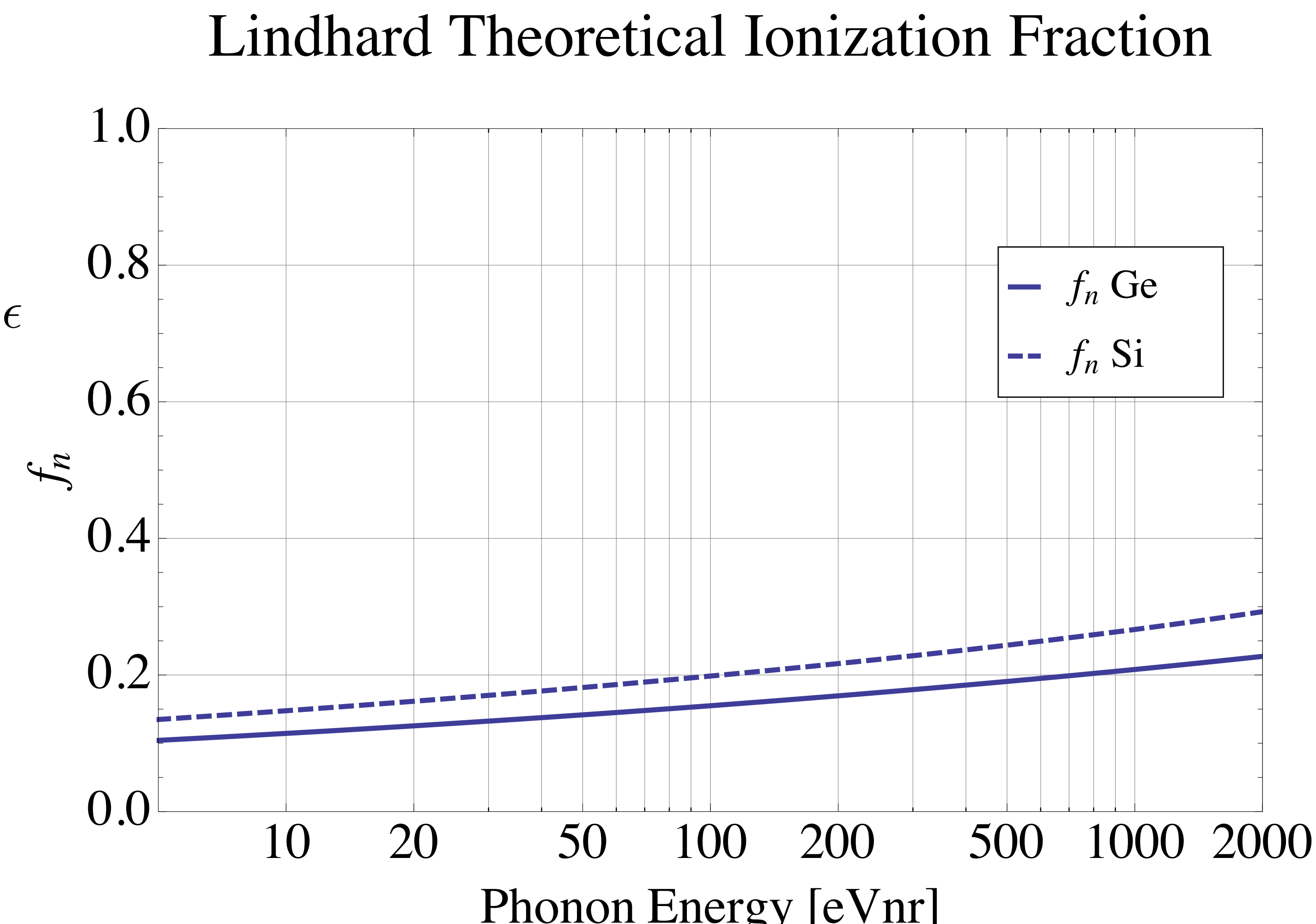
$$f_n = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

Fraction of recoil energy deposited in target converted to ionization signal

$$k = 0.2$$

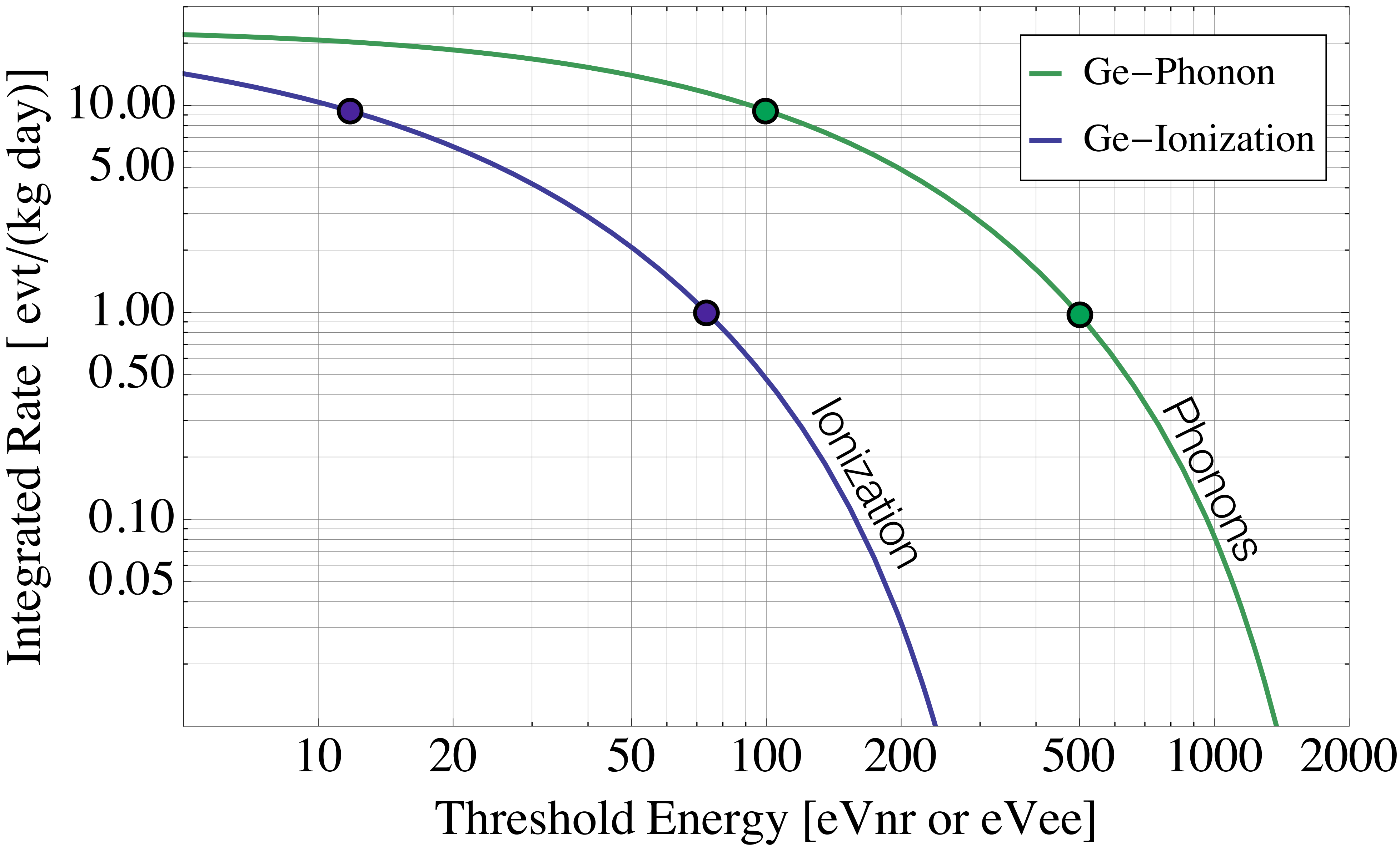
$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = 11.5\, T\, Z^{-7/3}$$



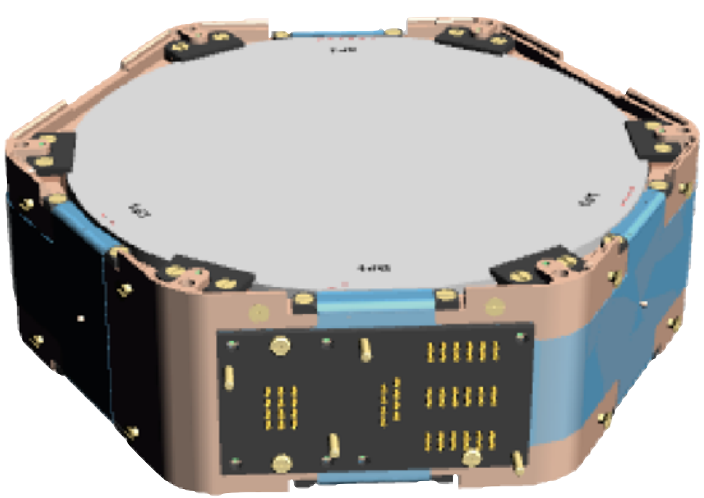
Event rates at ATR for phonon and ionization

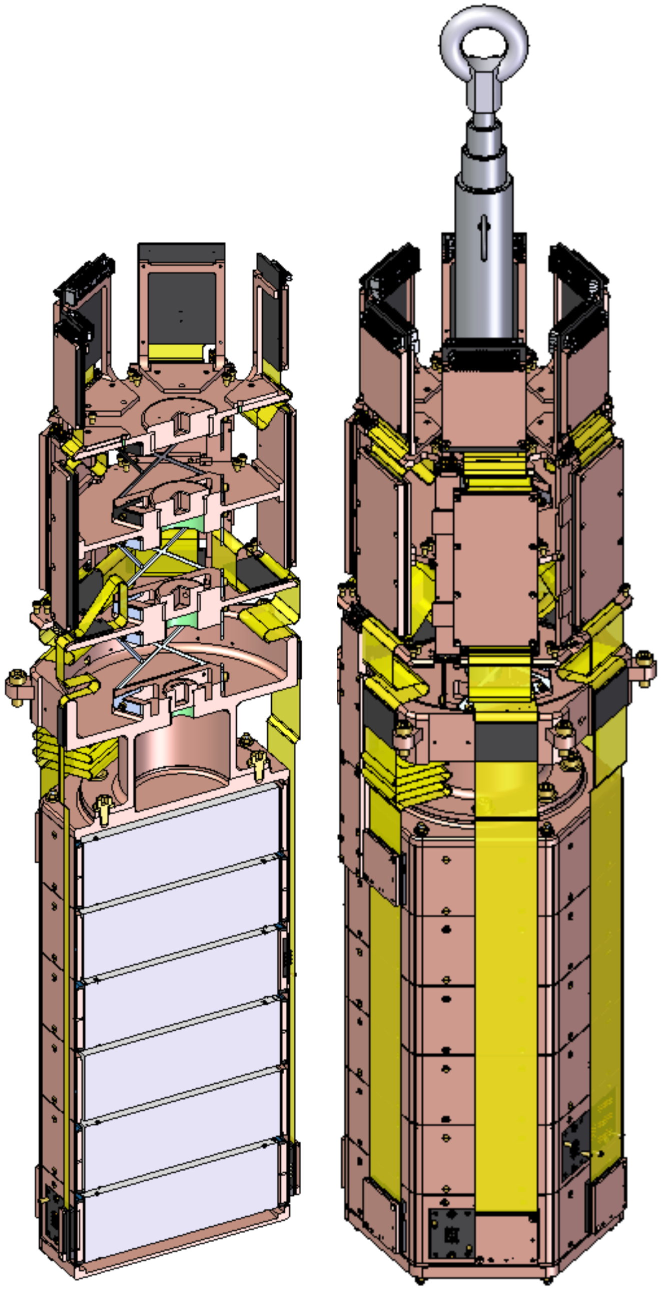
Ionization readout requires much lower thresholds for the same rates



Ricochet Phase 1: SuperCDMS Tower at a Reactor

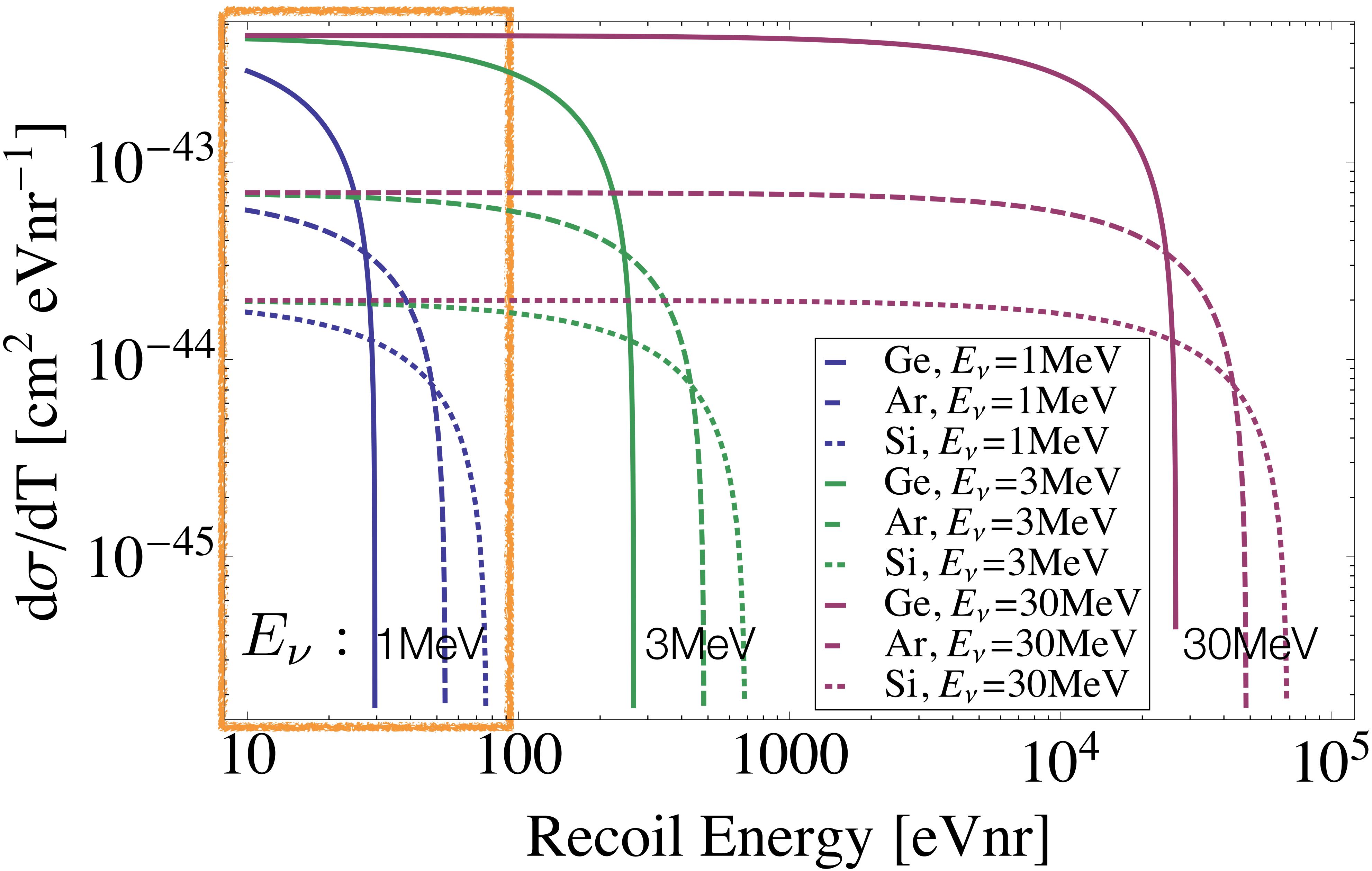
- Leverage R&D and Engineering being done by the SuperCDMS G2 Experiment.
- 1 Tower holds 6 detectors, ~100 eVnr Threshold
- 4 Si Detectors = 2.4kg Si = 11 CE**ν**NS events per day
- 2 Ge Detectors = 2.8kg Ge = 26 CE**ν**NS events per day
- **>7000/1000/400** events per month at the SONGS, ATR, and MIT reactors
- **>20** events per month at the SNS (for comparison)





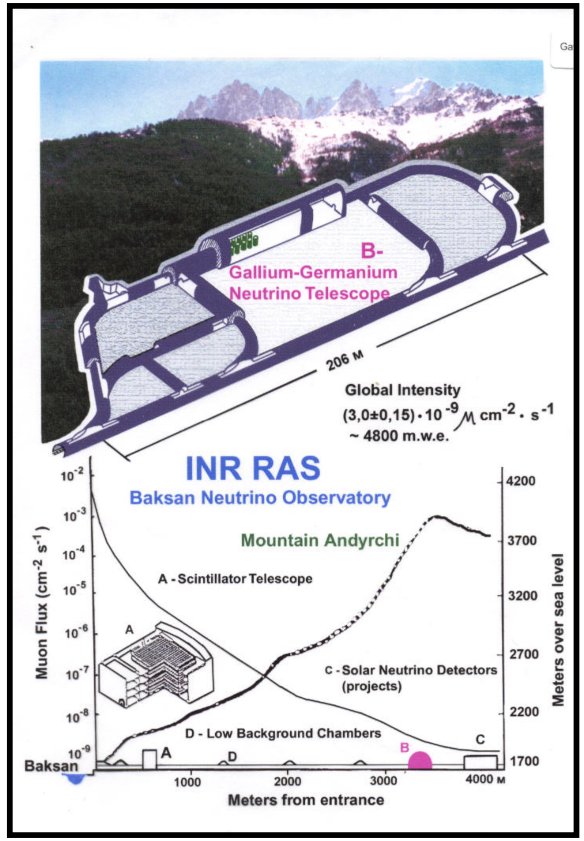
Ricochet Phase 2: CEνNS with ~1 MeV neutrinos

Need Thresholds of 10's of eV!



Ricochet Phase 2: ~1 MeV neutrino sources

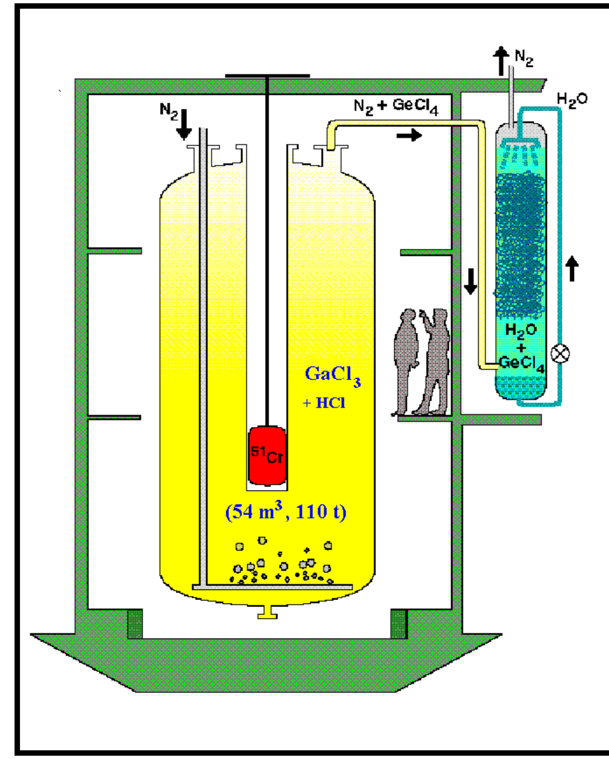
- Ideal mono-energetic sources have been constructed for experiments previously (SAGE, GALLEX), of order 1 MCi activity.
- Jon Link will talk about the ^{51}Cr program
- A Ricochet detector at SOX might also be an interesting possibility.



SAGE

^{71}Ga + ν_e --> ^{71}Ge + e$^-$

Use of ^{37}Ar and ^{51}Cr



Gallex/GNO

^{71}Ga + ν_e --> ^{71}Ge + e$^-$

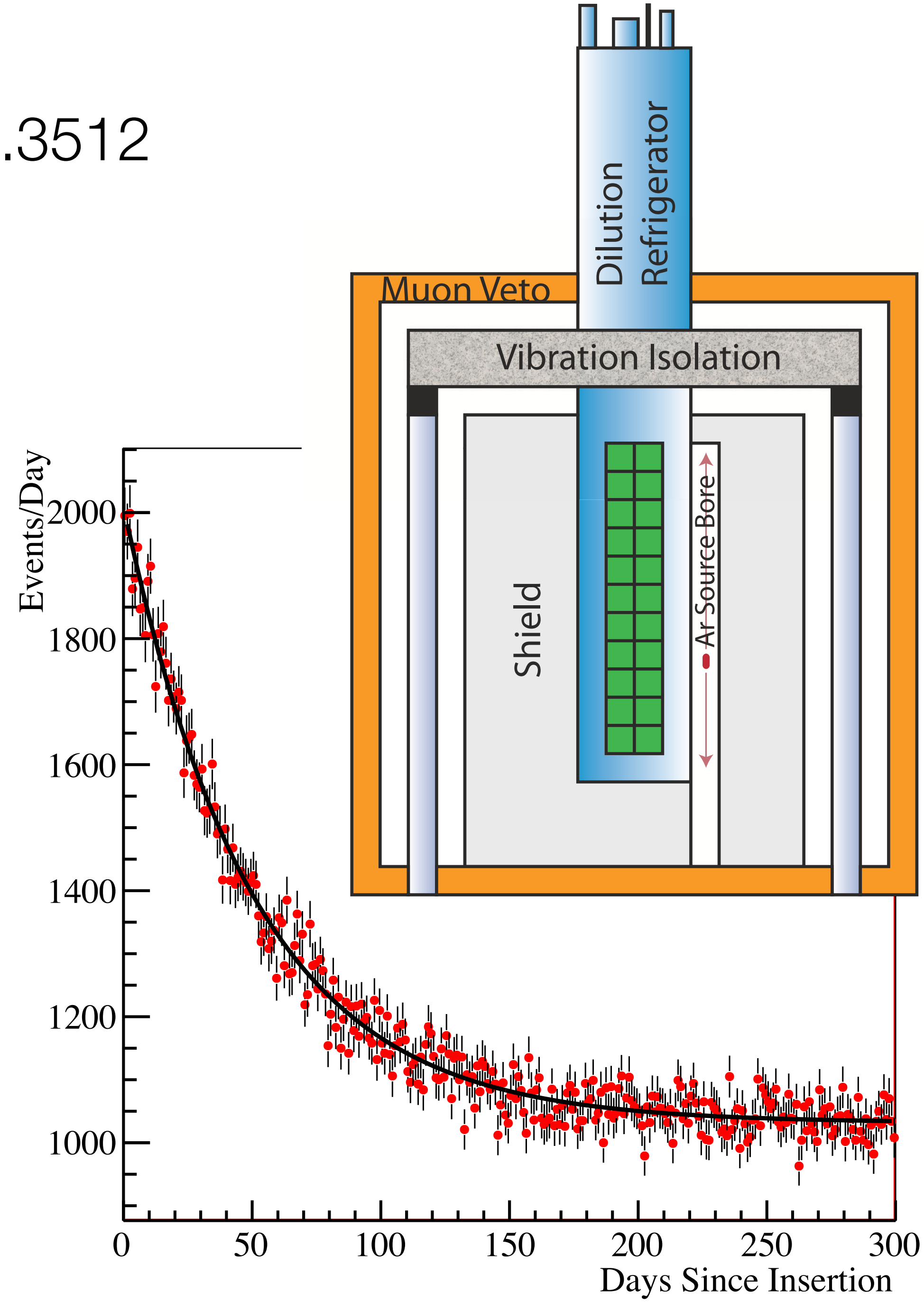
Use of ^{51}Cr

Source	Half-Life	Progeny	Production	E_ν
^{37}Ar	35.04 days	^{37}Cl	^{40}Ca(n,α)^{37}Ar	811 keV (90.2%), 813 keV (9.8%)
^{51}Cr	27.70 days	^{51}V	n capture on ^{50}Cr	747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)
^{65}Zn	244 days	^{65}Cu	n capture on ^{64}Zn	1343 keV (49.3%), 227 keV (50.7%)

Ricochet Phase 2: CEνNS with ~1 MeV neutrinos

arXiv:1107.3512

- Array of 10,000 elements with ^{37}Ar or ^{51}Cr source just outside shield (10 cm closest distance).
- Measuring time of 300 days (for ^{37}Ar, equivalent of 50 days signal, 250 days background).
- Background rate of 1 event/kg/day in energy region of interest
- R&D needed, would be a “smoking gun” experiment done if charged current experiments saw a signal.



Ricochet Phase 2: CEνNS with ~1 MeV neutrinos

- Sensitivity study performed on 10,000 element array (500 kg Si, 200 kg Ge), ^{37}Ar or ^{51}Cr source.
- Assumed 300 day measuring time with background rate of 1 event/kg/day.
- Analysis on shape + rate (bulk result from shape)
- Mock signal also tested.

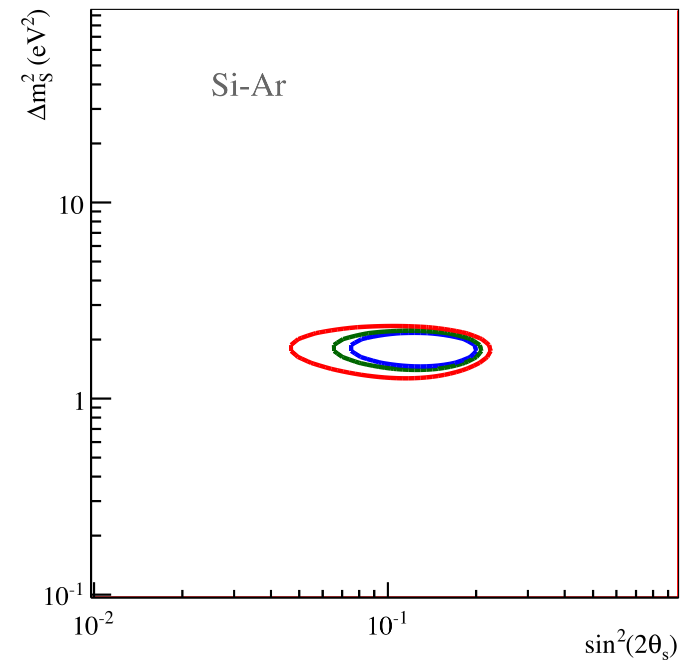
arXiv:1107.3512

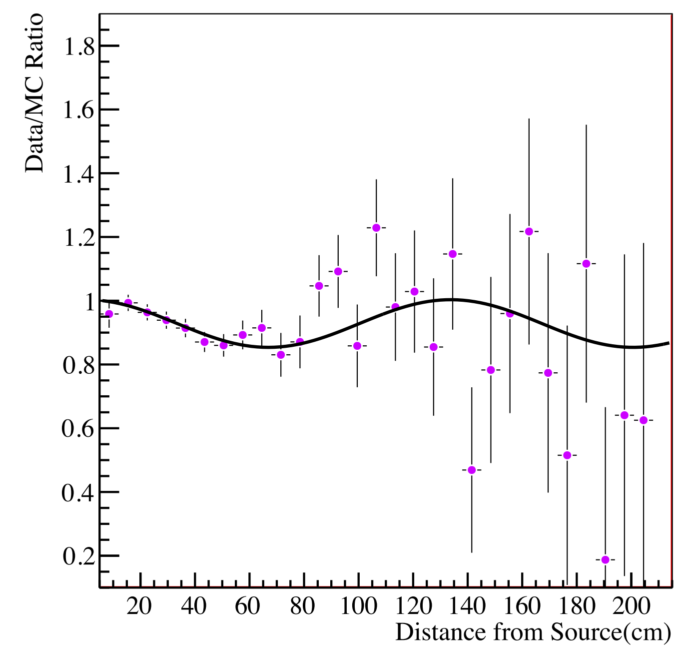
Alternate Measurements

coherent scattering measurement

$\sin^2\theta_W$ measurement

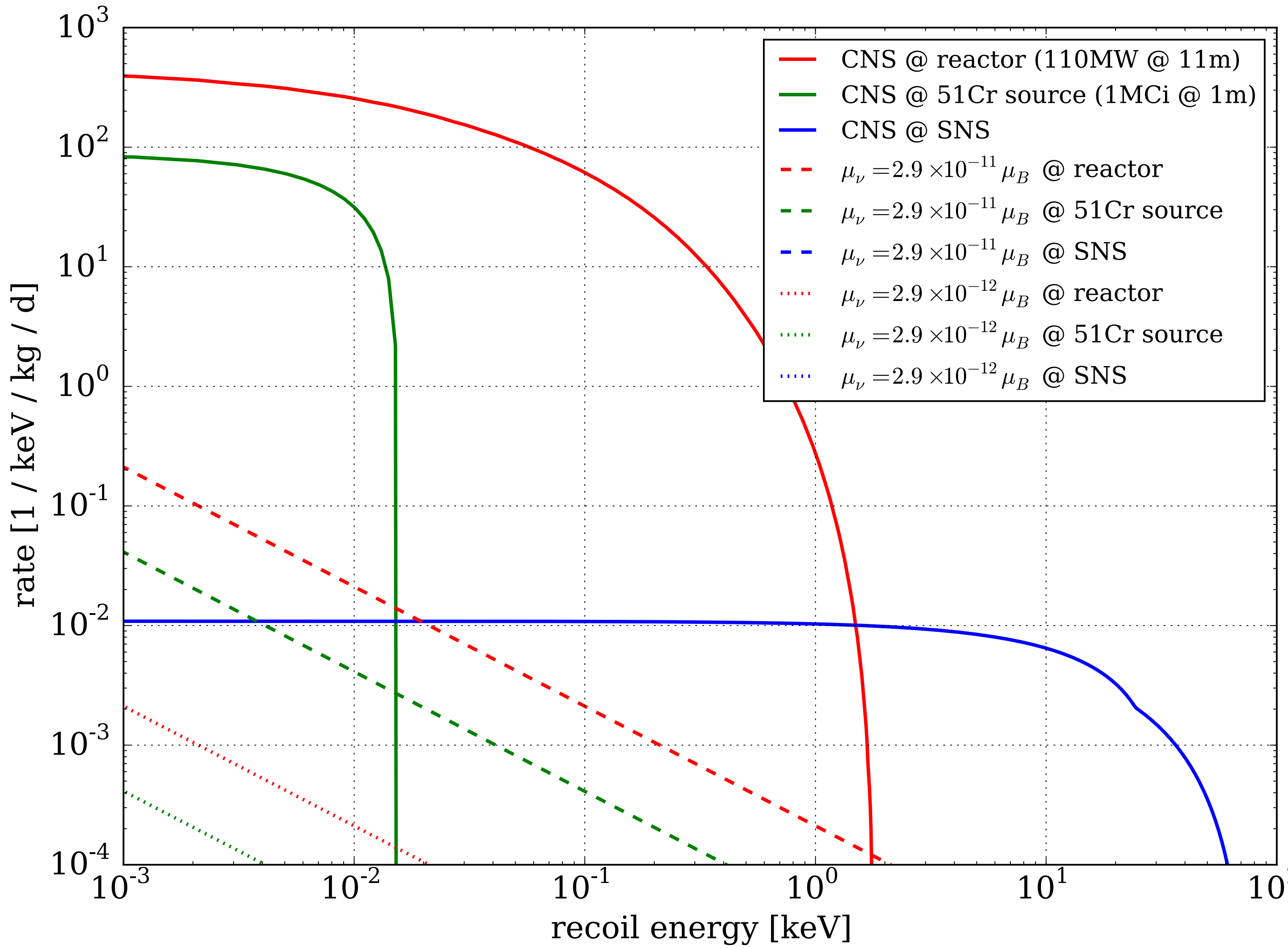
dark matter detection





Neutrino Magnetic Moment?

- CE**ν**NS is a background to neutrino magnetic moment searches!
- Look above CE**ν**NS cutoff?
- Large masses needed…
- See Jon Link's talk for a Xe-based experiment.



Conclusions

- Coherent neutrino scattering is a promising way to look for new physics.
- Low-threshold phonon detectors derived from the SuperCDMS program are a very promising technology for CE**ν**NS and associated science.
- We have calculated the CE**ν**NS rates for several reactor sites and developed a GEANT4 Monte Carlo (RicochetMC) that allows us to calculate the backgrounds expected from this experiment.
- Background calculations are still ongoing. Neutron backgrounds need to be modeled and measured.
- A future experiment with a mono-energetic EC source would be an ideal way to perform a sterile neutrino search.

Backup Slides

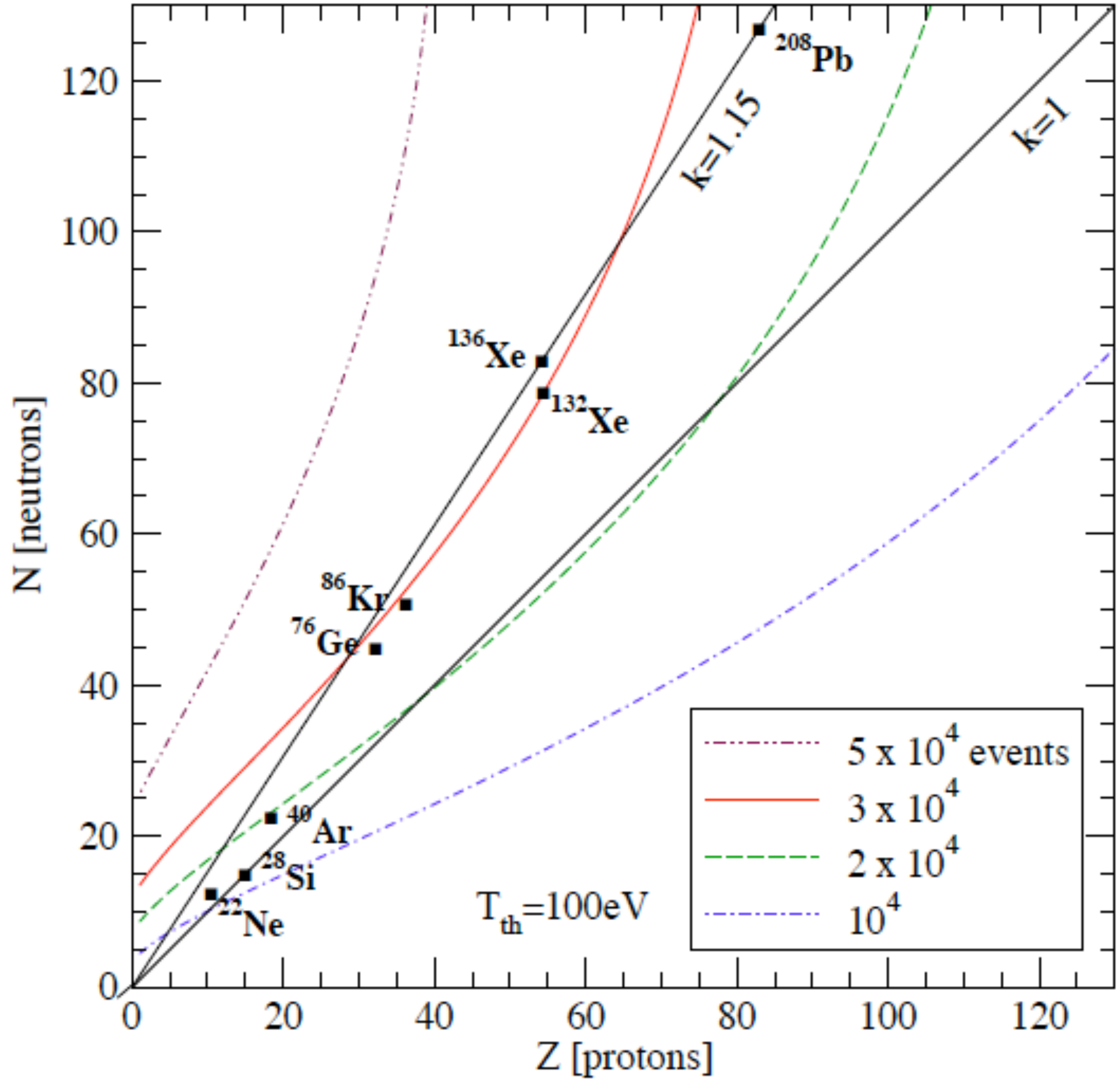
NSI Sensitivity

$$\frac{\partial\sigma}{\partial T}(E_\nu, T) = \frac{G_f^2}{\pi} M \left(1 - \frac{MT}{2E_\nu^2}\right) \left((Zg_v^p + Ng_v^n) \boxed{+ (A+Z)\epsilon_{ee}^{uV} + (A+N)\epsilon_{ee}^{dV}}\right)^2$$

- Non-Standard Interactions are a way to search for physics beyond the standard model by parametrizing deviations in the interaction rates between particles
- Our proposed experiment can place world-leading limits on some of these parameters

Need Two Targets for Optimal NSI Sensitivity

- The important term is the difference in the N/Z ratio
- Ge and Si are an ideal choice!
- Plot: difference in event rates for Ge and Si with a 100 eV threshold



Barranco 2005, hep-ph/0508299

Potential Sensitivity